PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : B25J

A2

(11) International Publication Number: WO 95/32842

(43) International Publication Date: 7 December 1995 (07.12.95)

(21) International Application Number: PCT/US95/06376

(22) International Filing Date: 19 May 1995 (19.05.95)

(30) Priority Data:
08/245,873 19 May 1994 (19.05.94) US

(71) Applicant: EXOS, INC. [US/US]; 2A Gill Street, Woburn, MA 01801 (US).

(72) Inventors: AN, Bin; Apartment 2, 21 Newport Street, Arlington, MA 02174-6206 (US). MASSIE, Thomas, H.; 22 Court Street, Vanceburge, KY 41179 (US). VAYNER, Vladimir; 89 Windsor Avenue, Acton, MA 01720 (US).

(74) Agent: PASTERNACK, Sam; Choate, Hall & Stewart, Exchange Place, 53 State Street, Boston, MA 02109 (US).

(81) Designated States: AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, JP, KE, KG, KP, KR, KZ, LK, LR, LT, LU, LV, MD, MG, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, MW, SD, SZ, UG).

Published

Without international search report and to be republished upon receipt of that report.

(54) Title: SENSORY FEEDBACK EXOSKELETON ARMMASTER

(57) Abstract

An exoskeleton sensory feedback apparatus that senses position and force information from a user and applies forces and torques to a limb. The apparatus has the same number of degrees of freedom as the limb to which it is attached. This is achieved through the use of remote center mechanisms, compliant mechanical design elements and portable self contained electrical motor-cooling systems.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	GN	Guinea	NE	Niger
BE	Belgium	GR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgystan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LU	Luxembourg	TD	Chad
CS	Czechoslovakia	LV	Latvia	TG	Togo
CZ	Czech Republic	MC	Monaco	TJ	Tajikistan
DE	Germany	MD	Republic of Moldova	TT	Trinidad and Tobago
DK	Denmark	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	US	United States of America
FI	Finland	MN	Mongolia	UZ	Uzbekistan
FR	France			VN	Viet Nam
GA	Gabon				

SENSORY FEEDBACK EXOSKELETON ARMMASTER

Background of the Invention

This invention relates to sensory feedback mechanical exoskeletal controllers and more particularly to force feedback anthropomorphic arm controllers.

Mechanical controllers convert human motions into system control information. For instance, a computer mouse converts the hand motion of a computer user into control information within the computer. User hand motions in the x and y directions are sensed by the mouse and converted into information which is used to control the cursor location on the computer screen. Therefore a computer mouse is a mechanical controller that translates planar hand motions into control information.

The computer mouse is a simple mechanical controller. More complex mechanical controllers exist for converting additional human motions and forces into control information. For instance, past mechanical controllers include robot hands (Salisbury, J.K., "Design and Control of an Articulated Hand," *International Symposium on Desing and Synthesis*, Tokyo, Japan, 1984) and force-reflecting controllers (Bejczy, A., Salisbury, J., "Controlling Remote Manipulators Through Kinesthetic Coupling," *Computers in Mechanical Engineering*, pp. 48-60, July, 1983; Agronin, M.L., "The Design of a Nine-string Six-degree-of-freedom Force-feedback Joystick for Telemanipulation," *Proceedings of the NASA Workshop on Space Telerobotics*, Pasadena, CA, 1987, pp. 341-348) for robot arm manipulation.

The kinematic forms of these prior mechanical controllers forced a design tradeoff. These systems could either closely model the kinematics of the slave device (i.e. a robatic hand or robotic arm) or could model the kinematics of the human controller (i.e. the operator's hand or the operator's arm) or could be a generic controller such as a joystick which usually does not model either the human arm or hand or the slave robot. In systems designed to model the kinematics of the slave device, the translation of user interactions into

control information is relatively simple. Every change in the controller represents a change for the slave with possibly some translation or scaling. But since the kinematics of the controller model the slave, their applications are limited to the type of slave robot they model.

To utilize the wider range and dexterity of user motion, the mechanical control system may model the kinematics of the operator. This approach may require a more complex translation of user motion, since the kinematics of user libm such as the arm or hand differ from the kinematics of the slave system. But through the use of digital computers, the translation is easily achieved. As a result the user can utilize the wider range and dexterity of natural user motion in controlling the slave.

A generic mechanical controller such as a joystick usually does not model the kinematics of either the human user of a slave robot. As a result, the output from such controllers usually must be translated to control a slave. The advantage of this type of controller is that they can control a wide variety of slaves. The drawback is that they are very difficult to use because they do not have the kinematic similarity to either the slave of the user's arm or hand.

The difficulty arises in the design of the mechanical controller. If the user input is the motions and forces of the arm, the system must model the mechanics of the human limb, in other words the system must be kinematically equivalent to the arm. This entails following the full range of motion of the shoulder, elbow, forearm and wrist.

In order to be kinematically equivalent to the user arm or hand, the control system must take one of two approaches. Either the system must have the same degrees of freedom of the arm but be tightly coupled to the arm (i.e. be anthropomorphic) or the system must have more degrees of freedom than the arm and therefore can be loosely coupled to the arm so that the user motion can be computer from the controller input. If the system has more degrees of freedom than the arm, the system grows in complexity and size, thereby decreasing the utility of the system. This complexity increases as force and touch feedback is added to the system. If the system has the same degrees of

freedom as the arm, then the design is simplified but the resulting system must be tightly coupled to the arm. Any misalignment between the system and the user imposes kinematic constrains on human joints and causes great discomfort and obstruction of the natural anatomic movement. Because the center of rotation for human joints are very difficult to locate and may also change with the joint angle, true joint axis alignment is practically impossible. Therefore the coupling required is so tight that it reaches the point where the system must be actually located in the same location as the arm. Clearly the system can't be colocated within the same space as the arm so a perfectly anthropomorphic system cannot exist.

The present invention acheives an anthropomorphic mechanical control system. The invention solves the coupling problems through the use of design features which allow compliance in the control system. As a result, the kinematics of the present invention model the arm, allowing the full range of user motion, while at the same time retaining an overall simple anthropomorphic design. In addition, the motion of and the torque on the user's joint can be simply measured and controlled. There is no need for kinematic conversion.

The preferred embodiment of the present invention was the design and development of an exoskeleton arm master (EAM) which provides control signals to robot arms or computer images and force feedback to the human operator. The EAM allows robot arms working in unstructured environments to gently touch objects, and finely manipulate them without exerting excessive forces.

Thus it is a goal of the present invention to provide a mechanical control system which models the kinematics of the the human arm. An additional goal of the present invention is to provide a control system which models the arm both kinematically and anthropormorphically. Further goals include providing mechanisms in the system to provide force feedback to the user and additionally providing a system that is comfortable to wear and easily donned and doffed.

Brief Description of the Drawings

The foregoing and other objects and advantages will become apparent from the following detailed description read in conjunction with the drawings in which:

Fig. 1 is a cross-sectional diagram showing a side view of the EAM.

Fig. 2 is a cross-sectional diagram showing a front view of the EAM.

Fig. 3 is a cross-sectional diagram showing a top view of the cable remote center mechanism.

Fig. 4 is a cross-sectional diagram showing a front view of the cable remote center mechanism.

Fig. 5 is a cross-sectional diagram showing a side view of the back attachment.

Fig. 6 is a cross-sectional diagram showing a front view of the back attachment.

Fig. 7 is a cross-sectional diagram showing a back view of the back attachment.

Fig. 8 is a cross-sectional diagram showing both a front and side view of the drum mechanism.

Fig. 9 is a cross-sectional diagram showing a cut away view of the motor with water jacket.

Fig. 10 is a cross-sectional diagram showing both a front and side view view of the heat exchanger and pump.

Fig. 11 is a cross-sectional diagram showing a system view of the motor cooling system.

Summary of the Invention

In accordance with the present invention, an exoskeleton mechanical controller for sensing position and movement and force information and applying motions, torques and forces to a limb. The controller comprises at least one remote center drive mechanism for applying a torque to one of a selected degrees of freedom of the limb. The remote center drive mechanism

applies this torque remotely from the center axis of the selected degree of freedom. A remote center drive mechanism is disclosed for remotely applying a torque about a center. The mechanism comprises a means for supplying force or motion, a means for sensing force and motion, a means for surrounding an object centered about the axis to which the torque or motion is to be supplied, and a means for conveying the force or motion to the surrounding means thereby creating a torque or motion about the center. The conveying means can utilize a cable drive mechanism.

Also disclosed is a stand alone portable cooling system for cooling electrical motors. The cooling system comprises a reservior for holding coolant allowing the coolant to disipate heat. A first transmission means conveys the coolant to the electrical motor. A fluid jacket surrounds the electrical motor and allows coolant to circulate around the motor, removing heat, and then exit the fluid jacket. A second transmission means conveys the coolant back to the reservior. The system is self contained and portable. The system can also utilize active means such as fans and thermoelectric coolers for removing heat from the reservior. The cooling system can also include a pumping means for actively circulating the coolant.

Detailed Description of the Preferred Embodiment

Herein we propose an exoskeletal mechaincal controller which models the kinematics of the human arm while retaining an overall anthropomorphic design.

The preferred embodiment of the present invention is an integrated 5 degree-of-freedom (DOF) prototype EAM which can be used with various robot arms to study the interaction of robot arms with complex tasks in unstructured environments. The present invention can also be used to control and study the interactions between a computer image of a virtual object with tasks in a virtual environemnt. Table 1 summarizes the specifications of the system.

Description	The Force ArmMaster provides joint torque feedback to the human arm and torque, motion and touch commands to the slave or simulation.
Mechanism	The design uses a spatial mechanism to achieve its low profile and compact design while allowing full anatomic motions.
Joint Motions	Shoulder Flexion/Extension (F/E): 120° Shoulder Ab/Adduction (Ab/Ad): 120° Shoulder Int/External Rotation (I/E): 100° Elbow F/E: 100° Forearm Supination/Pronation (S/P): 100°
Powered DOF	Shoulder 3 Elbow 1 Forearm S/P 1
Torque	Shoulder Ab/Ad, F/E: 56.6 in. lb. Shoulder I/E: 20.3 in. lb. Elbow F/E: 14.0 in. lb. Forearm S/P: 3.4 in. lb.
Friction	Approximately 4% of torque
Backlash	Less than 0.2°
Weight	On the arm ~4 lbs On the waist (single arm) ~18 lbs On the waist (double arm) ~20 lbs
Size	Adjusts to fit most male and female arms.
Actuators	DC Motors
Sensor Outputs	Encoder output for each force feedback axis. Position sensing for passive motion axes.
Power Requirements	North America 115 VAC, 15 Amp, 60 cycle, single phase International Configurable

Table 1: Specifications of Sensing and Force Reflective ArmMaster.

Robot Interactions

The EAM was designed to provide force reflecting telerobotic control of both real and virtual slave manipulators. Its kinematics directly match robots that have human equivalent kinematics such as the Massachusetts Institute of Technology Whole Arm Manipulator (MIT-WAM) (Salisbury, J.K., Twonsend, W.T., Eberman, B.S., DiPietro, D., "Preliminary of a Whole-Arm Manipulation System (WAMS)," *Proc. IEEE International Conference on Robotics and Automation*, Philadelphia, PA, April 1988) robot resident at the

Johnson Space Center and other sites. Other robots can be controlled by mapping the kinematics of the EAM onto the kinematics of the slave.

Since the EAM can apply forces to both a location near the wrist and just above the elbow, the EAM provides a greater repertoire of feedback modes than a 6 DOF hand held joystick. A form of whole arm feedback can be produced by mapping the net force on each link of the slave robot to an equivalent force at the end of the link and then applying this equivalent force to the operator. This mapping can also be used to provide feedback for bracing.

EAM specifications were developed based on the specifications for the MIT-WAM, which is the expected slave robot at NASA Johnson. Based on information from Barrett Technologies, the MIT-WAM has the following performance characteristics.

Object Compliance:	1000-5000 N/m
Forces:	2 kgf (5 lbs) with arm extended
Peak Speed:	5 m/s (20 ft/s) at end tip
Acceleration:	6 g's at end tip

Table 2: MIT-WAM Specifications.

The following list discusses the engineering criteria upon which the specifications were developed.

Kinematics

The kinematic setup of the EAM provides for the human range of motion and also appropriately distributes a number of actuated degrees of freedom to effectively simulate slave-object interaction forces. Five DOF are used to fully simulate the interaction forces between a WAM robot and the environment. Also, while the EAM is able to apply forces to simulate contact with virtual objects, it is also unencumbering, allowing free motion when virtual objects are not being touched. Thus the system is light and freely back driveable, by

either active or passive means.

Transmission/Motors

In addition to carrying their own weight, the weight of the operator's arm and that of the device, the motors generate sufficient torque to display the interaction forces between the slave robot and the environment. This high torque leads to bigger motors and gearheads, which creates greater inertia, friction, weight, and lower back driveability. Incorporating transmission reductions into the design amplifies the torque, thus reducing the torque requirement of the motors.

Weight

Based on fatigue data, weight limits for the EAM were set. Fatigue or discomfort felt while using the device would detract from the overall perception of the environment, and therefore the device's performance.

Comfort

In order to provide a realistic simulation, the devices worn must feel transparent, and whatever body attachments exist must not impinge on the user's motion and comfort. Therefore, the EAM fits a wide range of body sizes, as any component that interfaces with the human body is adjustable. The EAM is designed to fit at least users in the range of 50 percentile female to 95 percentile male.

System Design

Exoskeletal ArmMaster

Referring to Figs. 1 and 2, the exoskeleton arm has five powered degrees of freedom. The first DOF 111 is mounted on the backpack by bracket 40 where motor frame 102 and motor 104 are fixed and drum 106 is driven to rotate about axis 107. This drum 106 is coupled to a bracket 112 by a link rod 108. Since drum 106, link rod 108 and bracket 112 are all supported by ball

bearing 110a, b, c, d, and e, a planar four-bar linkage transmission exists between bracket 112 and drum 106 where the rotation of bracket 112 about axis 113 is the output and the rotation of drum 106 is the input. Consequently, motor 104 drives bracket 112 about axis 113. This constitutes the first DOF 111 of the arm.

Drum 114, motor 116 and support bracket 118 form the second DOF 117 where drum 114 is fixed to bracket 112, bracket 118 and motor 116 are driven to rotate about axis 119.

Mounted to the rotating bracket 118 is the upper arm Cable Remote Center Mechanism (CRCM) 121. This upper arm CRCM is the third DOF where the motor bracket 120 is attached to bracket 118 through an adjustment 122. Motor 124 drives the upper arm cuff 126, the mechanism below it and the arm to rotate about the longitudinal axis of the upper arm 127. A bladder 125, inflatable by air liquid or other agent, is used between the cuff 126 and the upper arm of the user to compensate for any misalignment between the device and the shoulder.

The fourth DOF 131 is mounted to rotating cuff 126 through another adjustment 130 where motor 132 and its mounting frame 128 are fixed and drum 134 is driven to rotate about axis 135. Attached to this drum 134 is an adapter plate 136 to which the lower arm CRCM is mounted.

The lower arm CRCM is the fifth DOF 141. The motor mounting frame 138 is attached to adapter plate 136 through adjustment 140. Motor 142 drives cuff 144 to rotate about the longitudinal axis of the forearm 145. Mounted to this rotating cuff is a forearm extension rod 146 to which a hand cuff 150 is attached. The position of the cuff is adjustable through two adjustments 148 and 152.

Cable Remote Center Mechanism

As shown in Figs. 4 and 5, the concept had a rotating cuff about the forearm driven by a motor sitting outside the cuff. Since the cuff was rotating about an axis remotely located from the driving motor, this kind of design is

commonly referred to as Remote Center Mechanism (RCM).

Figs. 4 and 5 shows the Cable Remote Center Mechanism. It consists of a motor mounting frame 3, a driving capstans 1a and 1b connected to a motor 11, idlers 2a and 2b, a driven cuff 4, two pieces of cables 5a and 5b and the associated cable terminators 6 and tensioning mechanisms 7a, 7b and 12. Cable 5a starts from the terminator 6, travels along the outer surface of cuff 4, passes under and wraps around idler 2a clock-wise as shown in the front view. It continues traveling on and along the outer surface of cuff 4 and wraps clockwise around capstan 1a. It then goes over pulley 10a and finally terminates at tensioning block 7a. Cable 5b starts from the same terminator 6, travels along the other end of the cuff 4 and wraps around idler 2b, capstan 1b and pulley 10b and finally terminates at tensioning block 7b. Then the cable tension can be controlled by adjusting a tensioning screw 12 that pulls the tensioning blocks 7a and 7b together. Once the cable 5a and 5b are tensioned, the entire mechanism stays as an unit. The cuff is well supported by the cables, capstans and idlers in most directions. In the direction perpendicular to the cables are supported by two roller stops 12 and 13.

When motor 11 is energized, it will drive the cuff to rotate about its center 8. For instance if the motor 11 and the attached capstan 1a and 1b rotate CCW, cable will be forced to travel as shown by arrow 9a, which in turn drives cuff 4 in the same direction. Since the cuff is constrained by the capstans and idlers, it can only rotate about its longitudinal axis 8. The speed of rotation of the cuff is different from that of the capstan. The relationship is defined by the transmission ratio which in turn is defined by the diameters of the capstan, the cuff and the cables. By varying the ratio of diameters of the capstan and the cuff, a desired speed reduction and toque amplification can be achieved. This CRCM has a speed reduction built in by merit of its design, which reduces the need or requirement of additional external reduction.

The capstans 1a and 1b have threaded grooves on both ends to seat and guide the cable. These threads have the same pitch but opposite direction, left hand for one and right hand for the other. As a result, the load on the cuff is

purely rotational driving the cuff to rotate about its longitudinal axis. The cable is wrapped to both the capstan and the idler on both ends to constrain the cuff. Consequently the cuff is well constrained and can only be driven about its longitudinal axis.

When the motor is not energized, the cuff 4 can be rotated manually by a user about its axis 8. The rotation of the cuff forces the cable to travel with it and back-drives the capstan, the motor and the encoder attached to the motor end. Therefore, both the passive and active motions of the cuff can be monitored. This type of mechanism is commonly called a Remote Center Mechanism because there is no bearing support to the cuff on its axis of rotation. Although small bearings can be used for additional support and siffness under the cuff, in this particular design, there is no bearing support inside the cuff. The cuff is fully supported by cables, capstans and idlers outside of the cuff. The advantage of this particular design is that the same existing drive mechanism, i.e., ground frame, capstans, idlers and motor, can accept and drive cuffs of different diameters. If other support bearings were used, or more than one idler were used, the cuff diameter and thickness that could fit a particular drive mechanism would be fixed. This enables the changing of the cuff without modification of the underlying drive mechism.

Another advantage of this design is that the driven cuff is open, i.e., the cuff is only a portion of a cylinder. The open cuff design allows the user to easily don and doff the device. Alternatively, if a big ring bearing such as those manufactured by Kaydon Corporation of Muskegon, Michigan, were used, a full cylinder would have to be used for the cuff and therefore donning and doffing the device would be very difficult.

Bladder As Multi-degree of passive pivots and slider

An bladder 125 of Fig. 2, inflatable by air, jell, or other agent, was used at the upper arm CRCM. Kinematically it served as a combination of limited stroke slider and pivots and offered the compliance needed to conform to the arm's anatomy. It also offered a very friendly and comfortable interface

between the arm and the device. When properly inflated, the perceived stiffness of virtual objects would not decrease noticeably, if at all.

Back Attachment Design

Referring to Figs. 5, 6, and 7, the back attachment was built mainly with the harness from a Gregory backpack 30, a contoured spacer 32, a rigid base frame 34 and a series of adjustments. The adjustment in the vertical direction is achieved through a horizontal frame 36 which also holds heat exchanger 200 and water pump 201. Two sliding blocks 61a and 61b loosely connected to frame 36 by four shoulder screws 41a, 41b, 51a and 51b can slide up and down freely and locked in position by two thrum screws 43 and 53. The horizontal adjustment is implemented between previously described horizontal frame and a vertical truss 38. Similarly two sliding blocks 63a and 63b are loosely coupled to truss 38 by four small shoulder screws 45a, 45b, 43a and 43b. The sliding blocks can slide freely inside the two horizontal tubes of frame 36 and be locked in position by two thumb screws 47 and 49. Front-back adjustment is achieved by sliding bracket 40 in tube 70. The position can be locked by thumb screw 71. The exoskeleton is mounted to the back pack by three bolts at bracket 40.

The spacer 32 serves as an intermediate support between the rigid base frame 34 and the compliant backpack 30. The spacer is a three-dimensional structure that is planar on one side and curved to conform to body contours on the other side. The rigid frame 34 is mounted on the flat surface of the spacer. The backack is mounted to the contoured side of the spacer through a compliant, sheet plastic stay 31 which further distributes the load to the backpack evenly. A padded hip belt 33 is added to the Gregory pack to support the weight of the EAM device. Once it's properly tightened at buckle 35, it should carry approximately 80% of the overall weight. Although the two shoulder straps 65 also carries some weight, their main function is to keep the pack on the back of the user. Three adjustable buckles 39a, 39b and 37 can be used for proper fit and comfort. As an alternative embodiment, the EAM can

also be mounted to a stand or movable platform.

Drum Drive Mechanism

Fig. 8 shows a more detailed diagram of the drum drive mechanism. It shows a motor 210 connected to a hybrid speed reducer consisting of a gear reduction 322 connected to the motor 210 and a cable reduction 320 connected to the gear reduction 322. Cable 301 starts from the tensioning block 300, travels along the outer surface of drum 302, wraps around one end of capstan 304, over pulley 306 and back to the other end of capstan 304, wraps around it in the ooposite direction and back to tensioning block 300. Cable tension is controlled by adjusting the tensioning screw 303. The role of pulley 306 is to ensure the cable tension is balanced between both sides of the pulley 306 in order to maximize cable life.

For a force reflective device, a direct drive motor would always be preferred. Because of the torque requirement and the limitation of current motor technologies a speed reduction or a torque amplification must be used. In general the larger the reduction, the more torque amplification can be achieved, but more friction and backlash would be introduced. Both friction/stiction and backlash are very destructive for a force reflective device. For example, a one stage precision planetary gearhead has a friction 15% of the torque being transmitted and a backlash of 0.9 degree, a two stage gearhead transmission has a friction of 25% and a backlash of 1.8 degree and a three stage has a friction of 30% and a backlash of 2.7 degrees. On the other hand, a cable reduction is backlash free and has 99% transmission efficiency. Clearly cable reductions would be ideal for this application. However due to design constrains associated with cables, a single stage cable transmission of more than 15:1 reduction would be too large in size, and a two stage cable reduction would be complicated to design and difficult to assemble.

This hybrid reduction collects the merits of both the gear and cable reduction and minimizes their drawbacks. It is an excellent combination for force reflective devices where high torque, low friction and low backlash are

needed.

A hybrid transmission as described above, with the gearhead as the first stage and the cable reduction as the second stage, takes the advantage of both the gearhead and cable reduction while keep their drawbacks small. The hybrid transmission offers higher transmission efficiency than that of an equivalent gearhead because of the very high efficiency of a cable reduction. It gives very small backlash because it divides the backlash of the preceding gearhead by the cable reduction ratio. Take a hybrid transmission with a one stage gear and 7:1 cable reduction for example. The resultant efficiency is 85% for gears times 99% for cable reduction. It is 84%, much higher than that of a two stage gearhead, 75%. In addition the resultant backlash is only 0.1 degree, much better than that of a two stage gearhead (1.8 degree). In summary a hybrid cable-gear reduction, with the gear reduction as the first stage and cable reduction as the second stage, can produce excellent speed reduction, torque amplification with very low backlash while keeping its size compact and transmission efficiency relatively high.

In the current EAM design, for the larger and more muscular DOF, such as the shoulder F/E and Ab/Ad, where larger torque is needed and the joint is relatively less sensitive to friction, a two stage gearhead is used in conjunction to a cable reduction. For smaller joints such as upper arm I/E and elbow F/E, where smaller torque is needed and the joint is a little less sensitive to friction, a one stage gearhead is used with a cable reduction. For the forearm S/P where the joint is the weakest, a motor was directly mounted to a CRCM was used.

Fig. 8 also shows a cooling jacket 324 around the motor housing. Referring to Fig. 9, a cooling fluid such as water can be pumped through the gap between the cooling sleave 214 and the motor housing 216 to cool the motor. As a consequence, the continuous torque of the motor can be increased and therefore the output torque of the cable reduction is also increased.

Therefore, a hybrid transmission consists of a gearhead as the first stage and a cable reduction as the second stage and a water cooling method can be

used either together or separately to increase the output of a motor while keeping its backlash very small, efficiency relatively high and profile low.

Water Cooling System Design

The continuous torque of a motor is limited by the maximum current that can be pumped through the motor windings without damaging its insulation. When a current passes through a winding it generates heat, thus the winding temperature rises. When the winding temperature reaches a certain point, the winding insulation would fail. This temperature limit is determined by the material of the insulation. Therefore, to keep the motor operating properly, this damaging temperature must not be reached.

Normally, the motor winding temperature rise is solely determined by the amount of heat generated by the current and what is dissipated to the ambient air. The rate of heat dissipation is a function of the sum of thermal resistance between the rotor and the housing, the housing and the ambient air. Thermal resistance between the rotor and the housing depends on the air gap between these two parts. It is optimized by a motor manufacturer. Thermal resistance between the housing and the ambient air depends on the thermal properties of the housing and the ambient. Several techniques are possible to reduce the motor thermal resistance and thus increase the maximum continuous torque.

Direct Cooling Methods

Fill motor air gap with dielectric liquid: A dielectric liquid can be used to fill the air gap between the rotor and the housing. This decreases the thermal resistance between the rotor and the housing. This method could be used in conjunction of the subsequent methods to achieve an excellent motor performance. In addition this method does not significantly increase the bulk and weight of the motor assembly. The disadvantage of this method is the high cost and long lead time required for custom built motors.

Blow Air Though The Motor Air Gap: In many motors, a propeller is

attached to the shaft to create a air flow between the windings and the motor housing. In this case, the original two step heat dissipation becomes one step. The success of this method lies heavily on the high RPM of the motor shaft. Unfortunately, the force reflective exoskeleton motor is used mostly in a near stall condition. The motor does not generate sufficient rotor RPM to force an air flow through the motor air gap. In addition, the small air gap between the rotor and the housing may make this method impossible.

Blow Air Over The Motors: A stand alone fan can be mounted next to each motor to create air-over cooling. The disadvantage is the nosie, the added weight and the negative effect air flow itself on the users.

Attach Heat Sinks And Cooling Fins Directly On The Motors: Attaching heat sinking fins directly to the motor housings is simple and efficient. It does add weight to the motor assembly which must be either compensated for, or carried by, the user. But there is insufficient air circulation for this method to be practical.

Install a thermoelectric ceramic heat pump directly on the motors: A thermoelectric ceramic heat pump (also known as Peltier cooler) is a silicone chip that is capable of creating a temperature differential between its two surfaces. Attaching its cold surface to a motor housing and hot surface to a heat sink, it can be used to remove heat from the motor directly. The motor surface temperature can be decreased dramatically, well below the ambient, thus allowing for greater temperature gradient and more effective cooling. The disadvantages are its low efficiency and difficulty of mounting on a cylindrical surface. The typical efficiency of such a chip is about 50%. So to remove 100 watts of heat, a 200 watt chip would be necessary. Five motors would require a total of 1000 watts of electrical power. When 24v power supply is used the current would need to be 41A, requiring a huge electrical cable. The heat sink required for each chip would also add weight to the motor assembly.

Remote Cooling Methods

All the methods discussed above are direct heat dissipation methods

where heat is removed and dissipated at the motor. Another approach is to either transfer the heat to a remote place where it is then dissipated or to deliver a chilled coolant from a remote place to cool the motors. The back attachment is an excellent place to locate the remote chillers or heat exchangers. This approach allows the selection of a relatively larger chiller or heat exchanger because the back can tolerate more weight than the arm can. Although the overall weight might be larger, the weight on the arm (moving weight) would be smaller, which is a primary design objective. Consequently, this method achieves excellent cooling while keeping the weight on the arm to a minimum. There are two design issues in this approach: coolant delivery system design and chiller or heat exchanger design. Though they are not unrelated to each other, they are two separate design tasks. The following paragraphs describe several methods that can be used in our design.

Use A Water Pump On The Back: Like the previous method, a water pump can be used to pump water to the motors, which in turn remove the heat from the motors to a heat exchanger on the backpack. Water is an excellent coolant, its thermal conductivity is 81 times greater than that of air. In this method the thermal resistance between the motor housing and the water is practically zero. The heat in the water would be dissipated to the air either though a radiator or a chiller more effectively. We considered three different ways to make the heat exchanger.

A thermalelectrical chip and a heat sink and/or a fan can be used for the heat exchanger. As discussed previously, the power required for this system to work would not be practical.

A commercially available refrigeration unit could be used as the heat exchanger. This would be effective and simple because no design would be necessary. However, the smallest commercially available unit is about 11 lb., which is too heavy for the EAM.

A heat radiating radiator can be used for this purpose. They are small, light, very effective and are widely available. If needed, the efficiency of the radiator can be boosted by use of a fan.

Use A Back Mounted Air Pump To Blow Air To The Motors: An air pump mounted on the back can blow a stream of air over the motors. The air stream could be guided by hoses and jackets over the motor. Better results are achieved by scoring the motor housings to create a turbine effect and/or to increase the air contact area. The heated air can be conveniently exhausted to the ambient. Other benefits of this method are that it is free from leaks and worry, and the supply is plenty and free. The disadvantage is the noise generated by the pump and the exhaust of the heated air. Because of the small motor surface area and low temperature differential between motor surface and ambient air, a large air flow would be necessary to cool all five motors. To keep the weight on the arm small, the hoses, fittings and air jackets would also have to be small. Therefore, a high pressure air pump would be necessary. Then the noise would be of concern. The preferred method of cooling is a remote cooler using water circulating through the motors and out to an external heat exchanger. To achieve this, the motors were modified for use with a water jacket. Fig. 9 illustrates the electrical motor as used in the EAM. The motor 210 is a model RE 025-055-33-EBA201A manufactured by Maxon Interelectric AG, Brunigstrasse 220, CH 6072 Sachseln, Switzerland. If additional torque is require, a planetary gearhead 211 is attached to the motor output shaft 213. A model 2932.701-0005.0-000 manufactured by Maxon Interelectric AG, Brunigstrasse 220, CH 6072 Sachseln, Switzerland is used in the preferred embodiment. Also connected to motor 210 is a position encoder 212. A model HEDS5010 manufactuered by Hewlett Packard of Boise, Idaho is used.

The motor 210 is modified by the addition of a cooling sleave 214. The cooling sleave 214 surrounds the motor housing 216. This allows coolant to circulate through fitting 215a, between the sleave 214 and the motor housing 216, and back out through fitting 215b. Each end of the sleave 214 is sealed against the motor housing 216 by o-rings 217a and 217b.

As shown in the Figs. 10 and 11, a heat exchanger 200, a pump 201 and five water jackets 202a, b, c, d, and e for five motors are all connected in

series, and form an endless water loop. The heat generated by the motors is removed by water, carried to the exchanger mounted on the backpack and then dissipated to the ambient air through the exchanger. The heat exchanger 200 can be a relatively light aluminum radiator combined with a fluid reservior 203 combined with a bleeder valve 204. The cooled water is then pumped back to the motors by the pump to start another heat transfer cycle.

In selecting the water pump, rotary vein pumps, diaphragm pumps, gear pumps, and magnetic piston pumps were evaluated. A diaphragm pump was rejected after the first trial because it generated a loud noise and violent vibration associated with its pulsing action. The pump head and the motor of a magnetic piston pump are isolated because it is typically used with hazardous coolant. Since water is one of the clearest coolants, we do not need such an expensive system. Finally a plastic gear pump, a G-07012-20 manufactured by Cole-Palmer Instrumant Company of Niles, Illinois was selected because it was the lightest (only 10 oz), the quietest and the most economic.

It will be appreciated by those of ordinary skill in the art that the present invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The presently disclosed embodiment is therefore considered in all respects to be illustrative and not restrictive.

Claims

1. An external apparatus for attachment to a limb and having a selected numbers of degrees-of-freedom for applying torques to the limb comprising:

at least one remote center drive associated with one of the selected number of degrees-of-freedomm the remote center drive adapted to generate torques on the limb remotely from the center of rotation of the selected degree of freedom.

2. An system for cooling an electrical motor comprising:

a reservoir for holding said coolant including means for inputting said coolant and means for outputting said coolant;

means for cooling said coolant held in said reservoir;

first transmission means for conveying said coolant from said reservoir through a first means for water transmission; and

a fluid jacket surrounding said electrical motor including means for inputting coolant from said first transmission means and means for outputting coolant through a second transmission means for conveying said coolant;

whereby said electrical motor is cooled by said coolant which is circulated through said fluid jacket, said coolant then returned to said reservoir.

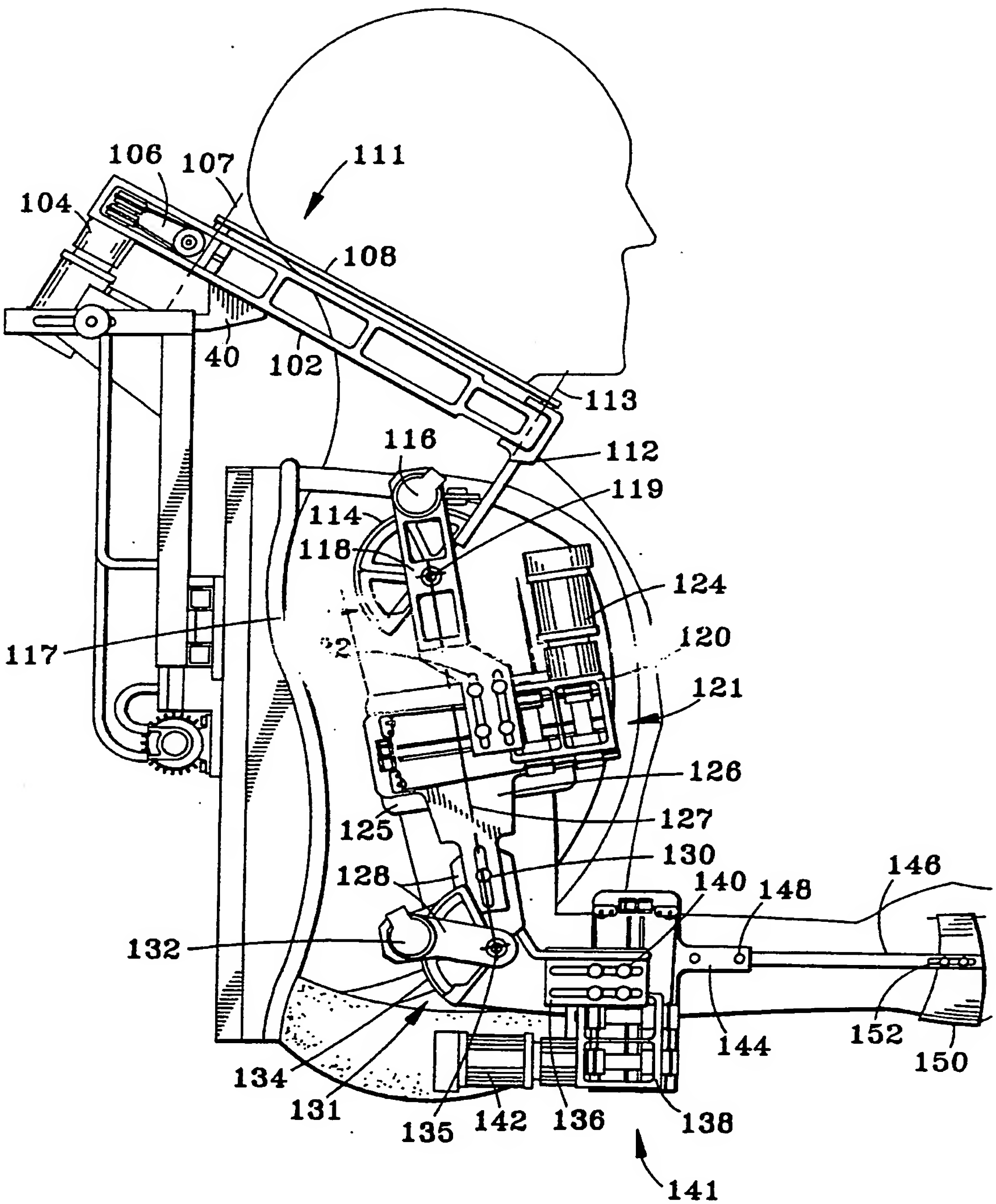
106
107
111
104
108
40
102
113
116
112
119
114
118
124
120
117
121
126
127
125
130
128
140
148
146
132
144
152
150
134
131
135
142
136
138
141

FIG. 1

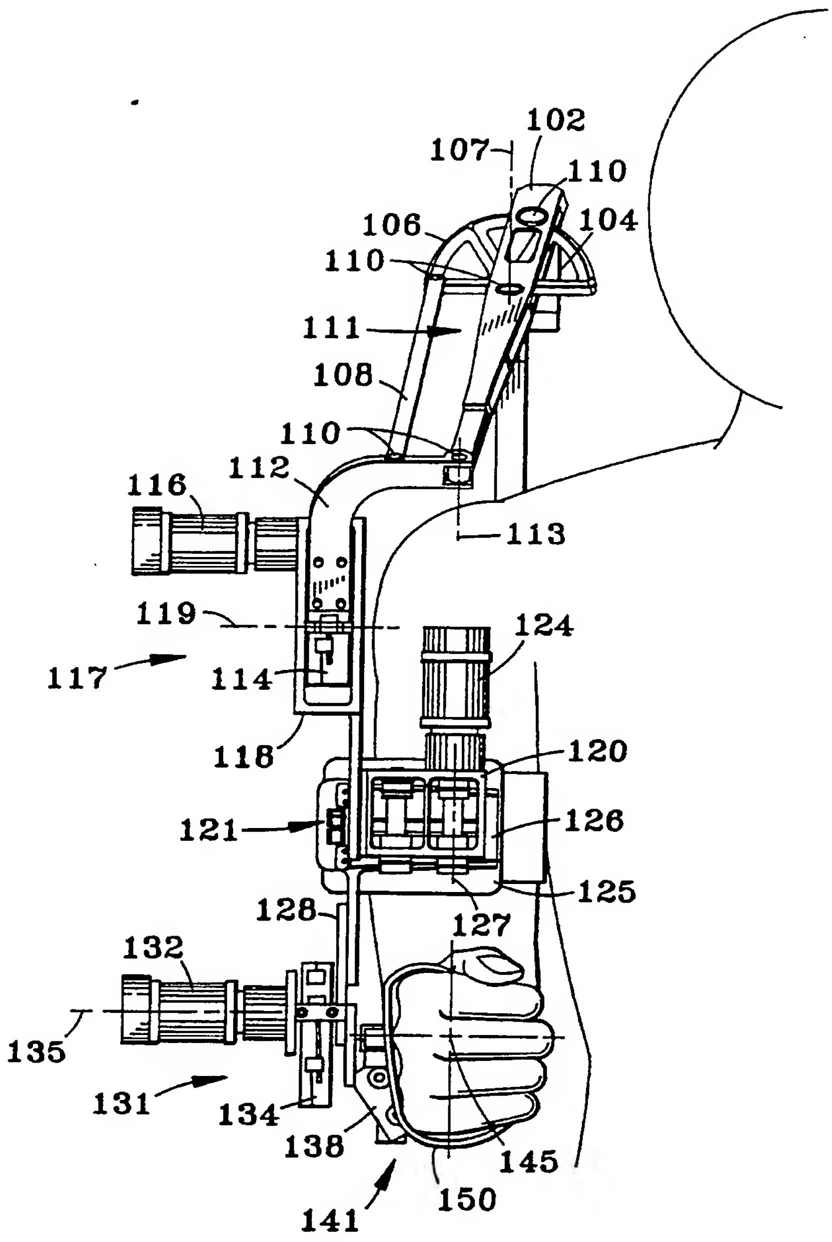
102
107
110
106
104
110
111
108
110
112
116
113
119
124
117
114
118
120
121
126
125
128
127
132
135
131
134
138
145
150
141

FIG. 2

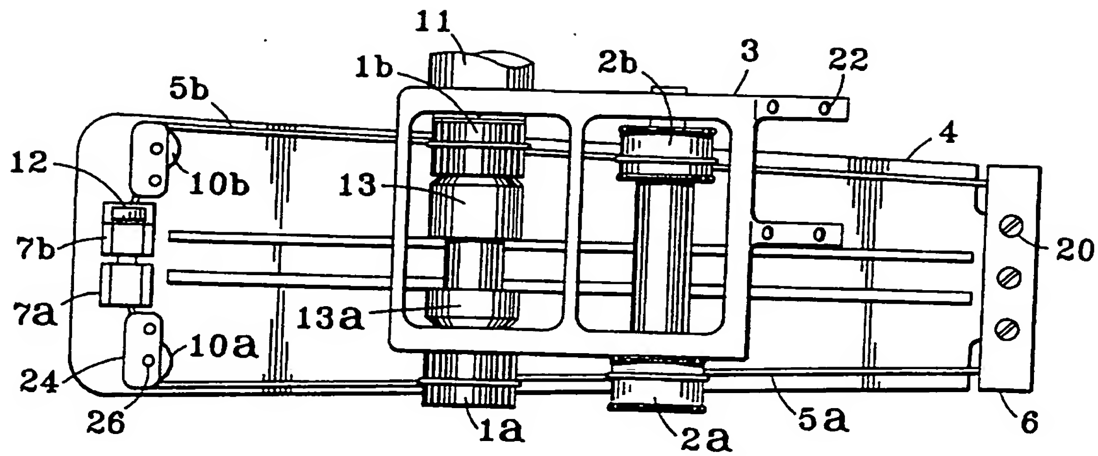
11
1b
2b
3
22
5b
4
12
10b
13
20
7b
7a
13a
10a
24
26
1a
2a
5a
6

FIG. 3

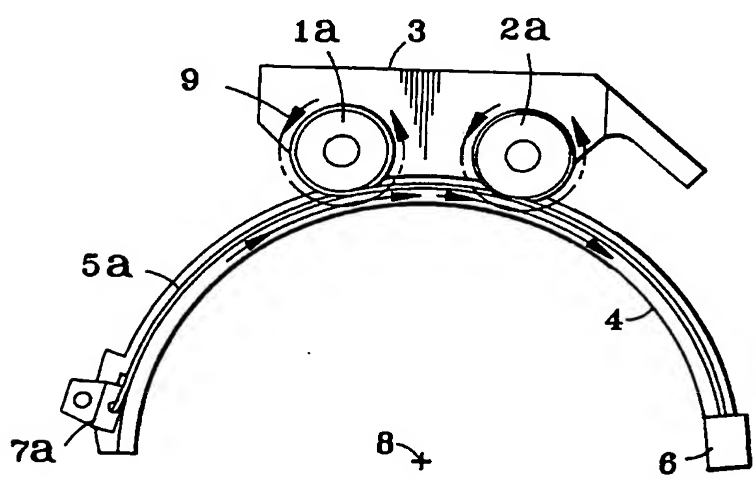
1a
3
2a
9
5a
4
7a
8
6

FIG. 4

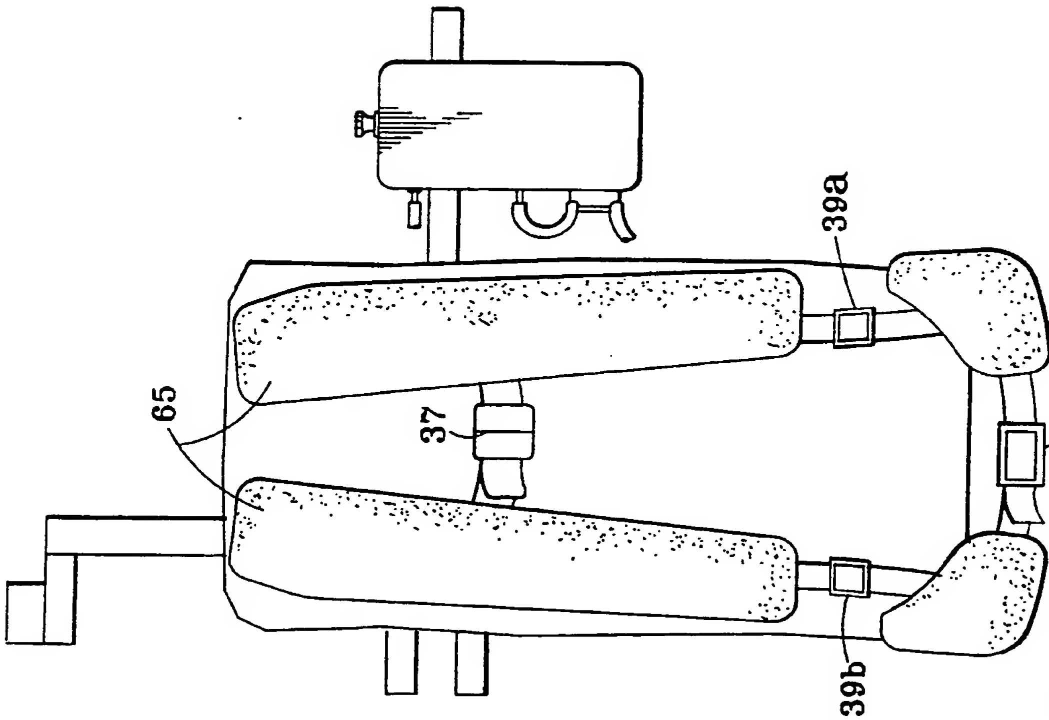

FIG. 6

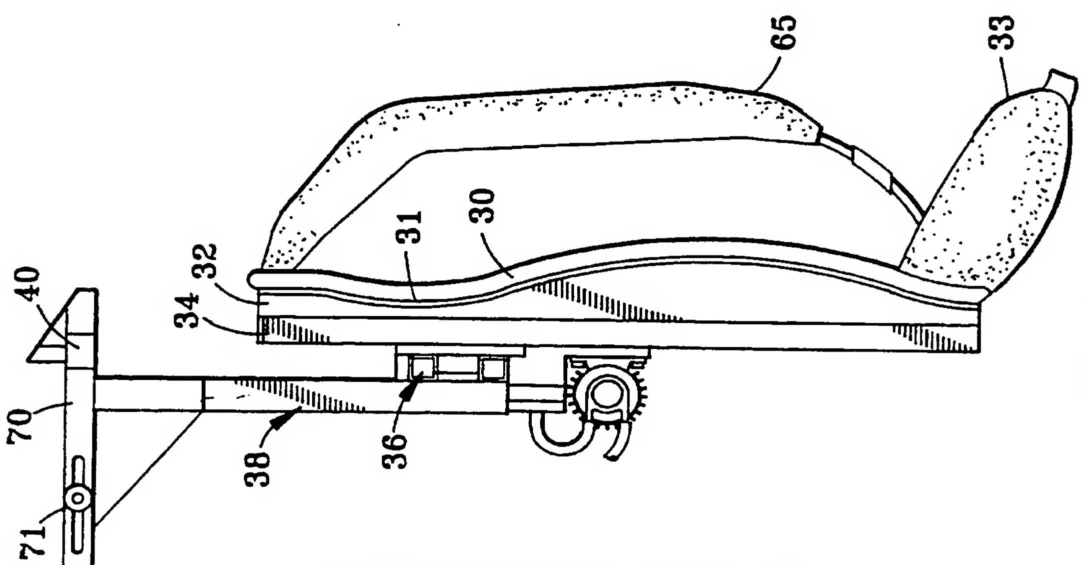

FIG. 5

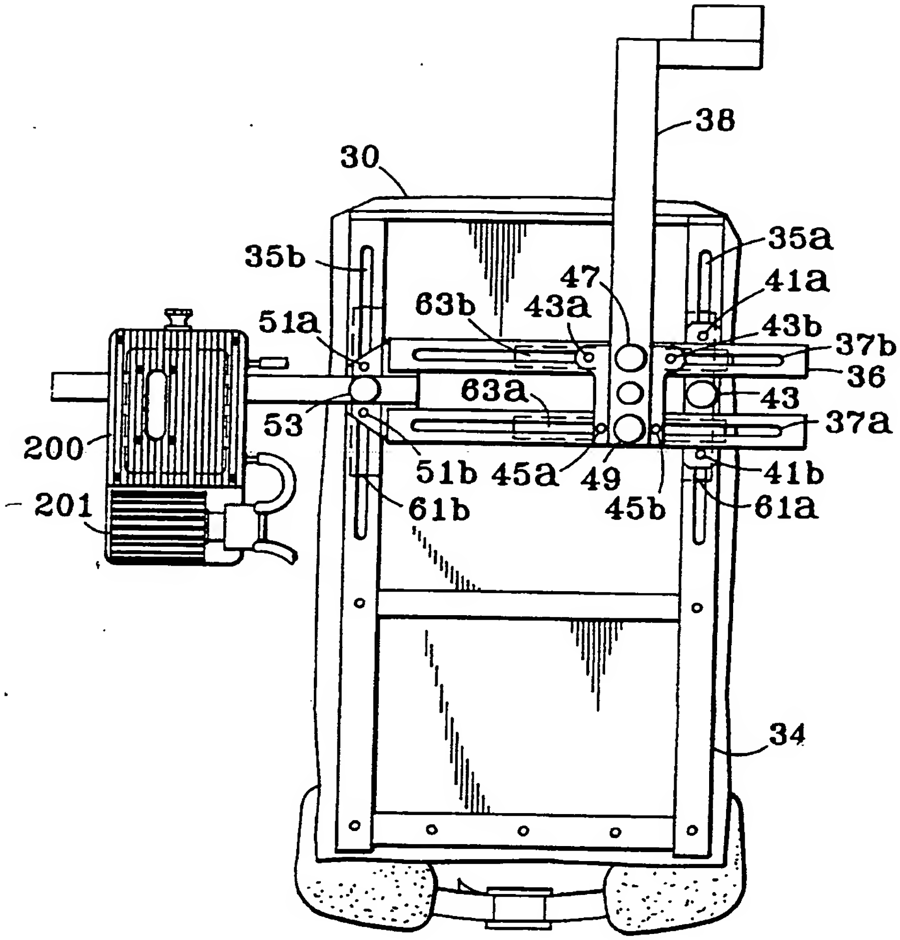

FIG. 7

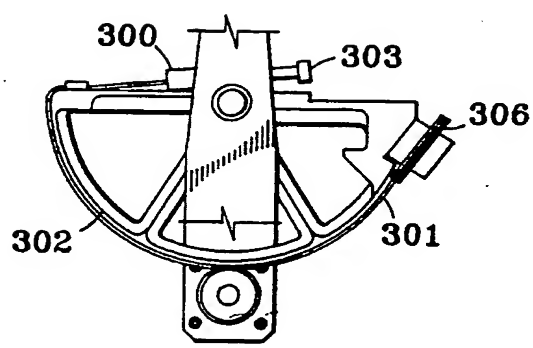

FIG. 8A

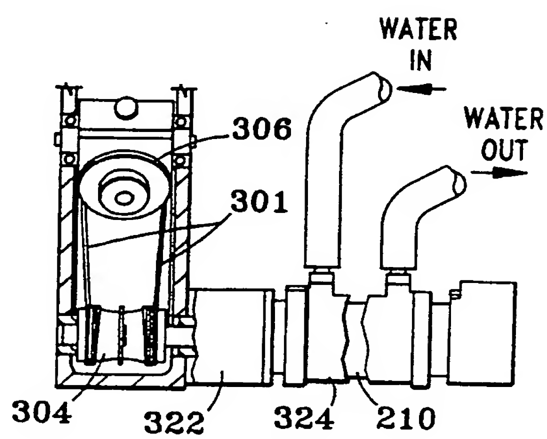

FIG. 8B

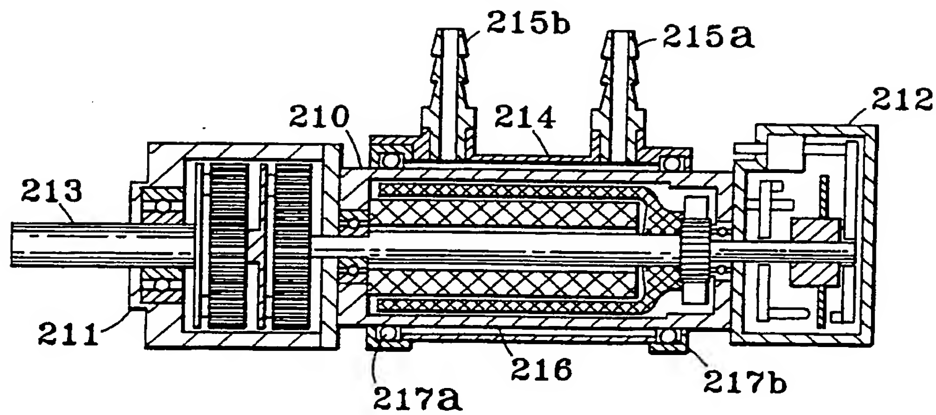

FIG. 9

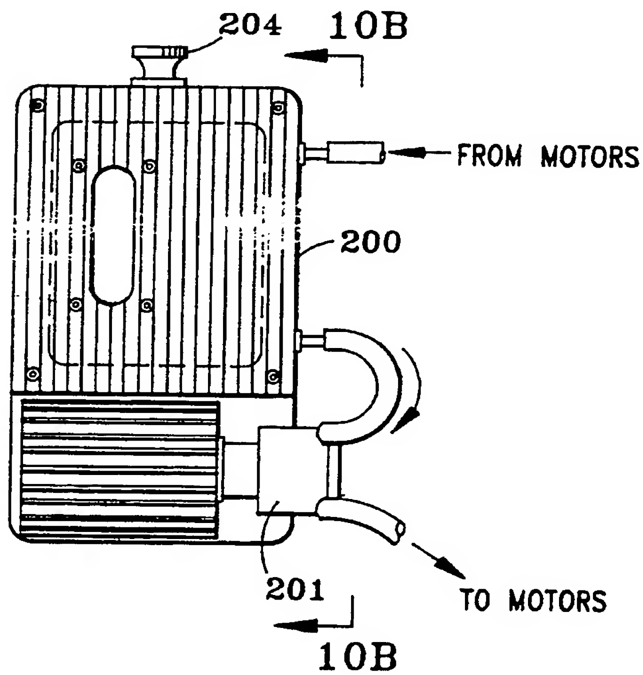

FIG. 10A

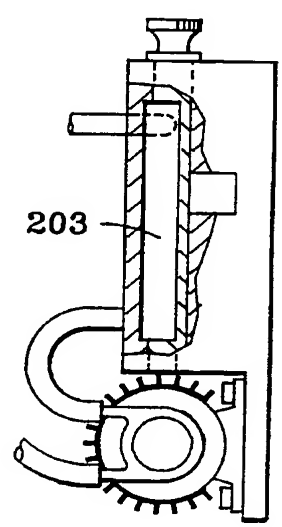

FIG. 10B

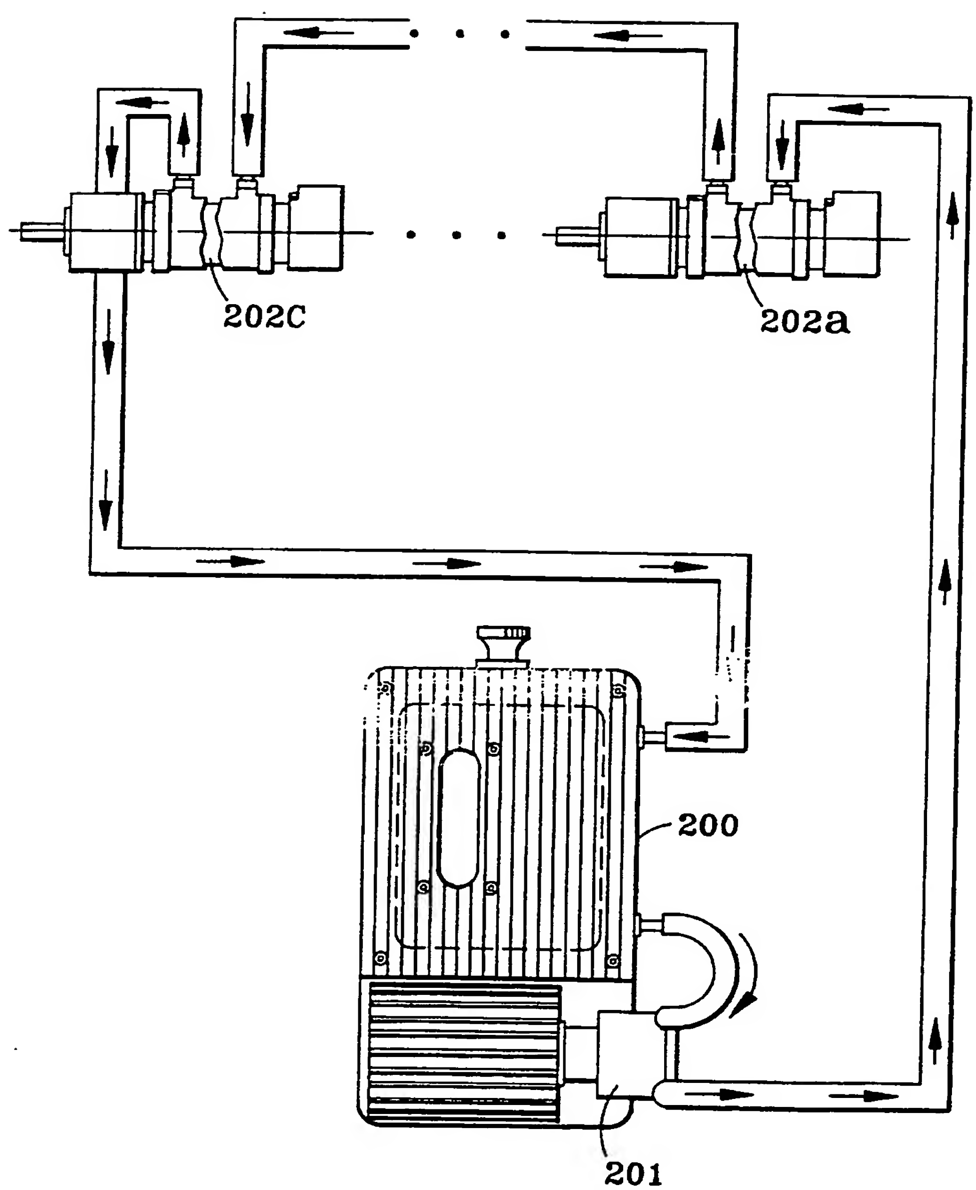

FIG. 11